

United States Patent Application For:

METHOD OF ETCHING A SHAPED CAVITY

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METHOD OF ETCHING A SHAPED CAVITY

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention pertains to a method of etching a shaped cavity in a substrate. In particular, the present invention pertains to a method for etching a shaped cavity, where the width of the shaped cavity is equal to or greater than the depth of the shaped cavity in the substrate.

2. Brief Description of the Background Art

Commonly owned, copending U.S. application Serial No. 09/372,477, filed August 11, 1999, of Podlesnik et al., provides a general method for forming a multi-part cavity in a substrate which is useful in many different micromachining applications. As disclosed by Podlesnik et al., a substrate is etched to a first predetermined depth to form a shaped opening. A conformal protective layer is then formed on at least the sidewall of the shaped opening. The protective layer comprises a material which has a different etch selectivity than the substrate material. If necessary, the protective layer is then anisotropically etched to remove portions of the protective layer which overlie the bottom of the shaped opening. Typically, at least a portion of the substrate at the bottom of the shaped opening is exposed prior to proceeding with subsequent etching. The substrate is then further etched to form a shaped cavity using an etchant gas which selectively etches the substrate relative to the protective layer.

For some applications it is desirable that the shaped cavity be formed to have a different shape than the shaped opening. For example, the opening to the cavity is tubular-shaped, while the shaped cavity has a width that is equal to or greater than its depth (*i.e.*, a round or horizontal elliptical shaped cavity). A shaped cavity of such dimensions is particularly difficult to form using dry etching techniques. Formation of round shaped

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1 cavities has previously been accomplished using wet etch techniques. However, in recent
2 years, the semiconductor manufacturing industry has been trending toward the use of dry
3 etch techniques because of process integration and environmental considerations. Due to
4 the difficulty of carrying the gaseous reactants into and reaction byproducts out of a cavity,
5 the use of dry etch techniques has been limited to the widening of already formed shaped
6 cavities by a relatively minor amount. Therefore, it would be desirable to provide a dry etch
7 method that would result in the formation of a shaped cavity having a width that is equal to
8 or greater than its depth. Lateral (as opposed to vertical) etch is dependent upon a number
9 of factors during the etching process, including the incoming angle of the etchant species,
10 the mean free path of the etchant species, and the ability of the etchant species to reach the
11 surface to be etched. Furthermore, byproducts of the etch process must constantly be
12 removed, and if these byproducts become trapped within a cavity being etched, etching may
13 slow to an unacceptable rate or stop entirely, particularly in the lateral direction. When a
14 conventional etch process is used, the desired lateral etch (if it can be achieved before
15 etching stops) is typically accompanied by an undesired deeper vertical etch. Therefore,
16 particularly during the etching of buried cavities, it is important to provide a means by which
17 etch byproducts can be evacuated from the etch cavity during the etching process, in order
18 to allow the desired amount of lateral etching without deepening of the cavity.

19 SUMMARY OF THE INVENTION

20 The present invention provides a method of dry etching a shaped cavity in a
21 substrate. The method is useful for aspect ratios as high as at least 3.5 : 1, and is particularly
22 useful where the width of the shaped cavity is equal to or greater than the depth of the
23 shaped cavity in the substrate, i.e. where the aspect ratio is less than 1.

24 We have discovered that it is necessary to control the process chamber pressure in
25 a particular manner during the performance of the etching process to permit etch byproduct
26 removal from the shaped cavity at a rate which reduces or avoids the buildup of etch

1 byproducts on interior surfaces of the shaped cavity. This permits continued etching of the
2 shaped cavity. In general, the method of the invention comprises etching of a shaped cavity
3 using at least two different process chamber pressures, including an initial process chamber
4 pressure, followed by continued etching of the shaped cavity using at least one decreased
5 process chamber pressure. The decreased process chamber pressure should be at least 25%
6 lower than the initial process chamber pressure, and in several embodiments is about 30 %
7 to 50 % lower than the initial process chamber pressure. An optional finishing or rounding
8 of the etched cavity may be carried out after shaping of the cavity, in which the process
9 pressure is increased ; the amount of increase is typically up to about 90 % of the initial
10 process chamber pressure.

11 During the etching of a shaped cavity, the process chamber pressure may be lowered
12 and then subsequently raised and relowered, as well, to provide for the removal of etch
13 byproducts during a given etching step.

14 The method of the invention is particularly useful in the etching of buried cavities.
15 The shaped cavity is typically formed to underlie a previously formed shaped opening.

16 The method of the invention can be performed as a continuous process, where the
17 process chamber pressure is gradually lowered or raised and lowered, or as a multi-step
18 process.

19 When the substrate is (single crystal)silicon, etching is typically performed using a
20 plasma containing reactive fluorine species. The etchant plasma is commonly generated
21 from a source gas comprising SF₆ and argon, provided at a flow rate which is process
22 equipment dependent, and at an SF₆ : argon ratio within the range of about 10 : 1 to about
23 2.5 : 1. When a round shaped cavity is desired, an SF₆ : argon ratio of about 4 : 1 provides
24 excellent results. Argon is used as an inert carrier for the SF₆, and ionized argon in
25 conjunction with a substrate bias may be used to drive reactive fluorine species generated
26 from SF₆ down through the shaped opening and into the shaped cavity.

27 Alternative primary etchant gases include gases such as CF₄, Cl₂, and HBr. Any of

1 the primary etchant gases may be used alone or in combination with a compatible other
2 primary etchant gas. For example, CF_4 may be used to replace SF_6 or may be added to SF_6
3 to obtain a desired effect. A primary etchant gas may be used in combination with an
4 additive gas, such as, for example, Ar, O_2 , HBr, Cl_2 , or N_2 , to provide better control over the
5 surface finish or etch profile of the shaped cavity. Depending on the particular effect
6 desired, the additive gas may be present during the entire duration of the method of the
7 invention, or it may be present only during a certain step or steps. The plasma source gas
8 may further include a substantially nonreactive, diluent gas, such as Ar, He, or Xe.

9 Examples of source gas combinations which are preferred for etching a silicon
10 substrate, and not by way of limitation, include $\text{SF}_6/\text{Ar}/\text{O}_2$; $\text{SF}_6/\text{Ar}/\text{HBr}$; $\text{SF}_6/\text{Ar}/\text{Cl}_2$; and
11 SF_6/Cl_2 . CF_4 may replace SF_6 or may be added to SF_6 in any of these source gas
12 combinations.

13 When the substrate is polysilicon, the plasma source gas typically includes SF_6
14 and/or Cl_2 . For a silicon dioxide substrate, the plasma source gas typically includes CF_4 or
15 NF_3 , and etching is typically performed at a temperature within the range of about 50°C to
16 about 100°C . When the substrate is silicon nitride, the plasma source gas typically includes
17 SF_6 . When the substrate is a metal (such as aluminum or an aluminum alloy), the plasma
18 source gas typically includes Cl_2 . When the substrate is polyimide, the plasma source gas
19 typically includes CF_4 and O_2 . All of these examples are intended to be non-limiting.

20 When a fluorine-containing etchant plasma is used at a temperature below 50°C , the
21 protective/masking layer preferably comprises silicon oxide. A silicon nitride
22 protective/masking layer may be used if the plasma source gas does not contain fluorine.
23 A metal or alloy protective/masking layer may be used if the plasma source gas does not
24 contain chlorine.

25 BRIEF DESCRIPTION OF THE DRAWINGS

26 Figures 1A - 1D illustrate one embodiment of the method of the invention.
27

1 Figure 1A shows a beginning structure 100 for practicing the general method of the
2 invention. This structure is a shaped opening 104 etched in a substrate 102 to a first
3 predetermined depth A.

4 Figure 1B shows the structure of Figure 1A following formation of a conformal
5 protective layer 106 on the sidewall 108 and bottom 110 of shaped opening 104.

6 Figure 1C shows the structure of Figure 1B after the protective layer has been
7 anisotropically etched to remove a portion of the protective layer which overlies the bottom
8 ~~108~~ of shaped opening 104.

9 Figure 1D shows the structure of Figure 1C after the underlying substrate 102 has
10 been etched using the multi-step etch method of the invention to form a shaped cavity 110
11 which underlies shaped opening 104. The shaped cavity 110 is etched to have a width B and
12 a depth C, where the width B is equal to or greater than the depth C. In particular, here,
13 ~~width B~~ is equal to depth C, so that the shaped cavity 110 is formed in a round, as shown.

14 Figure 2 shows a graph 200 of eccentricity (*i.e.*, the width of a shaped cavity divided
15 by its depth) as a function of the width of the overlying shaped opening, where curve 202
16 represents shaped cavities etched using a prior art etch process, and curve 204 represents
17 shaped cavities etched using the method of the invention.

18 Figures 3A and 3B, respectively, show examples of round and horizontal elliptical
19 shaped cavity profiles that can be obtained using the multi-step etch method of the invention.

20 Figure 3C shows a double spherical profile which is obtained by continued isotropic
21 etching of closely adjacent shaped cavities 302 and 304, in order to remove the substrate
22 material between the shaped cavities. By removing the substrate material between the
23 shaped cavities, a silicon "island" 306 is formed between shaped openings 308 and 310.
24 Such silicon islands are useful in, for example, DRAM capacitors, optical interconnects in
25 optoelectronic integrated circuits, micromachining, and submicron silicon-on-insulator (SOI)
26 applications.

27 Figure 4 is a schematic representation of an apparatus for practicing the present

1 invention which includes elements for computerized control of the apparatus used to carry
2 out the method of the invention.

3 DETAILED DESCRIPTION OF THE INVENTION

4 I. DEFINITIONS

5 As a preface to the detailed description, it should be noted that, as used in this
6 specification and the appended claims, the singular forms "a", "an", and "the" include plural
7 referents, unless the context clearly dictates otherwise. All percentages (%) listed for gas
8 constituents are % by volume, unless otherwise indicated.

9 Specific terminology of particular importance to the description of the present
10 invention is discussed below.

11 The term "cavity" typically refers to, but is not limited to, any three-dimensional
12 depression or buried space in a substrate, including, for example and not by way of
13 limitation, trenches, bowls, contacts, vias, tubes, holes, squares and other geometric shapes.

14 The term "eccentricity" refers to the ratio of the width of a shaped cavity to its depth.
15 For example, a perfectly round shaped cavity (*i.e.*, having a width exactly equal to its depth)
16 would have an eccentricity of 1.

17 The term "polysilicon" refers to polycrystalline silicon, which may be doped with,
18 for example and not by way of limitation, arsenic, phosphorus, antimony, or boron.

19 The term "substrate" refers to any material which can be etched using etching
20 techniques known in the art.

21 II. APPARATUS FOR PRACTICING THE INVENTION

22 The method of the invention is generally performed in a plasma etching apparatus
23 that is capable of enabling both anisotropic and isotropic etching, and is capable of
24 switching back and forth between the two types of etching. An example of such an apparatus
25 is the CENTURA® DPS™ polysilicon etch system, available from Applied Materials, Santa

1 Clara, California. U.S. Patent No. 5,753,044 issued to Hanawa et al. on May 19, 1998
2 contains a general description of an RF plasma reactor of the kind which may be used to
3 practice the invention described herein.

4 III. A METHOD OF FORMING A SHAPED CAVITY IN A SUBSTRATE

5 The present invention provides a method of dry etching a shaped cavity in a
6 substrate. Although the method is useful for aspect ratios as high as at least 3.5 : 1, it is
7 particularly useful where the width of the shaped cavity is equal to or greater than the depth
8 of the shaped cavity in the substrate, i.e. where the aspect ratio is less than 1. For example,
9 the shaped cavity can be etched to have a round shape, that is, the width of the shaped cavity
10 is substantially equal to the depth of the shaped cavity. Alternatively, the shaped cavity can
11 be etched to have a horizontal elliptical shape, that is, the width of the shaped cavity is
12 substantially greater than the depth of the shaped cavity.

13 We have discovered that it is necessary to control the process chamber pressure in
14 a particular manner during the performance of the etching process to permit etch byproduct
15 removal from the shaped cavity at a rate which reduces or avoids the buildup of etch
16 byproducts on interior surfaces of the shaped cavity. This permits continued etching of the
17 shaped cavity. In general, the method of the invention comprises etching of a shaped cavity
18 using at least two different process chamber pressures, including an initial process chamber
19 pressure, followed by continued etching of the shaped cavity using at least one decreased
20 process chamber pressure. The decreased process chamber pressure should be at least 25%
21 lower than the initial process chamber pressure, and in several embodiments is about 30 %
22 to 50 % lower than the initial process chamber pressure. The process chamber pressure may
23 be lowered and then subsequently raised and relowered, as well. Such pressure changes
24 permit etch byproducts formed during the etching process to be removed from the shaped
25 cavity during continued etching.

26 The method of the invention is particularly useful in the etching of buried cavities.

1 The shaped cavity is typically formed to underlie a previously formed shaped opening. In
2 a preferred embodiment method of the invention, the following steps are typically performed
3 prior to etching the shaped cavity: First, a substrate is etched to a predetermined depth to
4 form a shaped opening. Then, a conformal protective layer is formed over at least a portion
5 of the sidewall of the shaped opening. The protective layer comprises a material which has
6 a different etch selectivity than the substrate material. If necessary, the protective layer is
7 then anisotropically etched to remove portions of the protective layer which overlie the
8 bottom of the shaped opening. Typically, a portion of the substrate at the bottom of the
9 shaped opening is exposed prior to proceeding with subsequent etching, which occurs
10 laterally beneath the bottom of the shaped opening. However, etching through the substrate
11 laterally above the bottom of the shaped opening may be used, where the protective layer
12 covers only the upper portion of the shaped opening. The protective/masking layer
13 effectively preserves the profile of the protected portion of the shaped opening during
14 subsequent etching of the shaped cavity. One method for formation of the protective layer
15 is described in detail in commonly owned, copending U.S. application Serial No.
16 09/372,477, filed August 11, 1999, of Podlesnik et al., which is hereby incorporated by
17 reference.

18 The substrate is typically a semiconductor substrate, which is frequently silicon;
19 however, other substrates such as polysilicon, silicon dioxide, silicon nitride, metal (such
20 as aluminum or an aluminum alloy), polyimide, gallium arsenide, cadmium indium telluride,
21 doped silicon, doped polysilicon, doped silicon dioxide, tungsten, spin-on-glass (SOG),
22 polymers, metal alloys (such as Al/Si/Cu or Al/Ti); other specialized substrates (which
23 depend on the end use application) are contemplated as well. The silicon substrate may
24 include doped regions (*e.g.*, a buried dopant layer). Doped substrates may etch more readily
25 or less readily than undoped substrates, depending on the dopant and on the etchant species.
26 If silicon is used as the substrate material, a protective layer of silicon oxide can easily be
27 formed using techniques known in the art (such as those described by Podlesnik et al.).

1 The method of the invention can be performed as a continuous process, where the
2 process chamber pressure is gradually lowered or raised and lowered, or as a multi-step
3 process.

4 One embodiment of the method of the invention comprises a multi-step etching
5 method. In an initial cavity etch step, gaseous etchant species are introduced through a
6 shaped opening, having a protective layer over at least a portion of its surface, in order to
7 etch a shaped cavity. This embodiment is described with reference to a CENTURA®
8 DPS™ process chamber or a similar process chamber, where etching of the shaped cavity
9 is typically performed using an initial process chamber pressure within the range of about
10 20 mTorr to about 50 mTorr. Depending on the desired, predetermined shape of the cavity,
11 a substrate bias may be applied to assist in obtaining the desired shape. When increased
12 lateral etching is desired, a lower bias power, typically ranging from about 0 W to about
13 15 W, is commonly used. When increased vertical etching is desired, an increase in bias
14 power is used, so that the bias power typically ranges from about 20 W to about 200 W.

15 When the substrate is (single crystal)silicon, etching is typically performed using a
16 plasma containing reactive fluorine species. The etchant plasma is commonly generated
17 from a source gas comprising SF₆ and argon, provided at a flow rate which is process
18 equipment dependent, and at an SF₆ : argon ratio within the range of about 10 : 1 to about
19 2.5 : 1. When a round shaped cavity is desired, an SF₆ : argon ratio of about 4 : 1 provides
20 excellent results. Argon is used as an inert carrier for the SF₆, and ionized argon in
21 conjunction with a substrate bias may be used to drive reactive fluorine species generated
22 from SF₆ down through the shaped opening and into the shaped cavity. When vertical
23 etching is desired, a bias power within the range of about 20 W to about 200 W is typically
24 used; when lateral etching is desired, a bias power within the range of about 0 W to about
25 15 W is typically used. The newly formed shaped cavity may be used as a reaction chamber
26 during subsequent etching steps.

27 Typical process conditions for the initial cavity etch step fall within the following

1 ranges: a process chamber pressure ranging from about 20 m Torr to about 50 mTorr; a
2 source power ranging from about 600 W to about 900 W; a bias power ranging from about
3 0 W to about 15 W for more lateral etching, and ranging from about 20 W to about 200 W
4 for more vertical etching; a substrate temperature ranging from about 20°C to about 50°C;
5 and, a total gas flow of at least 100 sccm for a chamber volume of 35,000 cubic centimeters.
6 When the primary etchant gas source is SF₆, the SF₆ is commonly combined with Ar, at an
7 SF₆ : Ar ratio ranging from about 2.5 : 1 to about 10 : 1, with the flow rate of SF₆, typically
8 ranges from about 50 - 150 sccm.

9 Alternative primary etchant gases include gases such as CF₄, Cl₂, and HBr. Any of
10 the primary etchant gases may be used alone or in combination with a compatible other
11 primary etchant gas. For example, CF₄ may be used to replace SF₆ or may be added to SF₆
12 to obtain a desired effect. A primary etchant gas may be used in combination with an
13 additive gas, such as, for example, Ar, O₂, HBr, Cl₂, or N₂, to provide better control over the
14 surface finish or etch profile of the shaped cavity. Depending on the particular effect
15 desired, the additive gas may be present during the entire duration of the method of the
16 invention, or it may be present only during a certain step or steps. The plasma source gas
17 may further include a substantially nonreactive, diluent gas, such as Ar, He, or Xe.

18 Examples of source gas combinations which are preferred for etching a silicon
19 substrate, and not by way of limitation, include SF₆/Ar/O₂; SF₆/Ar/HBr; SF₆/Ar/Cl₂; and
20 SF₆/Cl₂. CF₄ may replace SF₆ or may be added to SF₆ in any of these source gas
21 combinations.

22 When the substrate is polysilicon, the plasma source gas typically includes SF₆
23 and/or Cl₂. When the substrate is silicon dioxide, the plasma source gas typically includes
24 CF₄ or NF₃, and etching is typically performed at a temperature within the range of about
25 50°C to about 100°C. When the substrate is silicon nitride, the plasma source gas typically
26 includes SF₆. When the substrate is a metal (such as aluminum or an aluminum alloy), the
27 plasma source gas typically includes Cl₂. When the substrate is polyimide, the plasma

1 source gas typically includes CF_4 and O_2 .

2 When a fluorine-containing etchant plasma is used at a temperature below 50°C , the
3 protective/masking layer preferably comprises silicon oxide. A silicon nitride
4 protective/masking layer may be used if the plasma source gas does not contain fluorine.
5 A metal or alloy protective/masking layer may be used if the plasma source gas does not
6 contain chlorine.

7 Returning to the embodiment described above pertaining to the initial cavity etch
8 step in a silicon substrate, after the initial cavity etch step, a second etching step is performed
9 in which the shaped cavity is enlarged in specific directions. The process chamber pressure
10 used in the second etching step is preferably about 25 - 50% lower than the initial process
11 chamber pressure. When a rounded shaped cavity is desired, decreasing the process
12 chamber pressure by about 30% provides excellent results. A process chamber pressure
13 within the range of about 10 mTorr to about 25 mTorr is typically employed during the
14 second etching step. To expand the cavity in a lateral (horizontal) direction relative to the
15 protected shaped opening, a bias power within the range of about 0 W to about 15 W is
16 typically used. The plasma source gas used in the second etching step is typically the same
17 as that used in the first etching step. Typical process conditions for the second etch step are
18 as follows: a process chamber pressure ranging from about 10 mTorr to about 25 mTorr;
19 a source power ranging from about 500W to about 800 W; a bias power ranging from about
20 0 W to about 15 W ; a substrate temperature ranging from about 20°C to about 50°C ; and
21 a total gas flow of at least 100 sccm total gas flow (for a chamber volume of 35,000 cc). For
22 efficiency purposes the etchant source gas is SF_6 / Ar, where the ratio of SF_6 : Ar ranges
23 from about 2.5 : 1 to about 10 : 1, where the SF_6 flow rate ranges between about 50 sccm
24 to about 150 sccm.

25 In an optional third etching step, the process chamber pressure is decreased still
26 further. Typically this step is a finishing or rounding step. The process chamber pressure
27 used is typically about 40 - 50% lower than the process chamber pressure used during the

1 second etching step. When a rounded shaped cavity is desired, decreasing the process
2 chamber pressure by about 50% from the process chamber pressure used in the second
3 etching step provides excellent results. A process chamber pressure within the range of
4 about 5 mTorr to about 12 mTorr is typically employed, and excellent results were obtained
5 using about 8 mTorr. The plasma source gas used in the optional third etching step is
6 typically the same as that used in the first and second etching steps. Typical process
7 conditions for the third etch step are as follows: a process chamber pressure ranging from
8 about 5 mTorr to about 12 mTorr; a source power ranging from about 350 W to about 650
9 W; a bias power ranging from about 0 W to about 10 W; a substrate temperature ranging
10 from about 20 °C to about 50°C; an SF₆/Ar etchant gas with an SF₆ : Ar ratio ranging from
11 about 2.5 : 1 to about 10 : 1, at an SF₆ flow rate ranging from about 50 sccm to about 150
12 sccm; and at least 100 sccm total gas flow (for a chamber volume of 35,000 cc).

13 In an optional etch finishing or rounding step, the process chamber pressure is
14 increased to provide the shaped cavity with an increased concentration of reactive species
15 at the surface of the cavity, after the removal of the etch process byproducts during the
16 second and (if applicable) third etching steps. The process chamber pressure used during
17 the etch finishing step need not be, but typically is lower than the initial process chamber
18 pressure for the first step. When a round shaped cavity is desired, increasing the process
19 chamber pressure to about 90%, of the initial process chamber pressure provides excellent
20 results. A process chamber pressure within the range of about 18 mTorr to about 45 mTorr
21 is typically employed during the optional etch finishing step.

22 The plasma source gas used in the etch finishing step may be of any composition
23 which provides a desired surface finish (roughness) or chemical composition. When surface
24 roughness is the only concern, the plasma source gas for a finishing step typically comprises
25 the same components as that used in previous etching steps. However, relative amounts of
26 the plasma source gas components may be adjusted. For example, the etchant species may
27 be the fluorine-containing species previously described, used in combination with argon;

1 however, the ratio of fluorine species to argon in the plasma source gas used in the etch
2 finishing step is typically lower than that used in the previous steps. In the etch finishing
3 step, the SF₆ : Ar ratio of the plasma source gas is typically within the range of about 1.5
4 : 1 and about 5 : 1.

5 When a round shaped cavity is desired, an SF₆ : Ar ratio of about 2.5 : 1 to about
6 3 : 1 provides excellent results. Surprisingly, we discovered that an SF₆ : Ar ratio of 2.0 :
7 1 does not provide good results.

8 Typical process conditions for the etch finishing step are as follows: a process
9 chamber pressure ranging from about 18 m Torr to about 45 mTorr; a source power ranging
10 from about 500 W to about 800 W; a bias power ranging from about 0 W to about 15 W;
11 a substrate temperature ranging from about 20 °C to about 50 °C; the SF₆ : Ar ratio
12 described above, where the SF₆ gas flow ranges from 50 sccm to about 150 sccm; and, at
13 least 110 sccm total gas flow (for a chamber volume of 35,000 cc).

14 In more general terms within the method of the invention, a shaped opening is
15 formed in a substrate, then the profile (*i.e.*, shape) of the shaped opening is preserved by the
16 formation of a protective layer (typically a conformal layer) over at least a portion of the
17 inner surfaces of the shaped opening. Subsequently, a shaped cavity, underlying the shaped
18 opening, is etched using a multi-step method performed at varying process chamber
19 pressures.

20 Formation of the protective layer over at least a portion of the shaped opening
21 generally preserves the shape of the opening and permits better control over the etch of the
22 shaped cavity.

23 Figures 1A - 1D illustrate the general method of the invention. Referring to Figure
24 1A, a shaped opening 104 is etched in a substrate 102 to a predetermined depth A using
25 etching techniques known in the art, depending on the substrate material. For example, but
26 not by way of limitation, the substrate 102 may be pattern etched to form shaped opening
27 104 using a conventional organic photoresist, an inorganic hard mask, or a combination

1 thereof.

2 As previously mentioned, the substrate 102 may comprise any material which can
3 be etched using techniques known in the art. The Examples provided herein are with
4 reference to silicon, although the general concepts of the invention can be applied to the use
5 of other substrate materials.

6 Referring to Figure 1B, a conformal protective layer 106 is formed on at least the
7 sidewall 108 of the shaped opening 104 using techniques known in the art, depending on the
8 composition of the protective layer. The protective layer 106 may reach all the way to the
9 bottom 110 of the shaped opening. However, in certain situations, such as for very high
10 aspect ratios ($\geq 20 : 1$), the protective layer 106 may not be deposited on the bottom 110 of
11 the shaped opening, depending on the feature size.

12 The conformal protective layer is deliberately formed on interior surfaces of the
13 opening, as distinguished from layers made up of reaction byproducts which are incidentally
14 deposited during various processing steps. To the extent that a byproduct layer is present
15 on the interior surface of the opening, the byproduct layer may be left there if its presence
16 serves a useful purpose, or it may be removed prior to application of the protective layer if
17 it would interfere with subsequent processing steps.

18 The protective layer 106 comprises a material having a different etch selectivity than
19 the substrate. In the case of a silicon substrate, a typical protective/masking layer may
20 comprise, but is not limited to, silicon oxide, silicon nitride, silicon oxynitride, titanium
21 nitride, aluminum, diamond, and polyimide. Silicon oxide and silicon nitride provide
22 excellent etch selectivity relative to silicon.

23 In the case of a silicon oxide substrate, a typical protective/masking layer may
24 comprise, but is not limited to, polysilicon, silicon nitride, titanium nitride, aluminum,
25 diamond, and polyimide. Polysilicon and silicon nitride provide excellent etch selectivity
26 relative to silicon oxide.

27 In the case of a silicon nitride substrate, a typical protective/masking layer may

1 comprise, but is not limited to, polysilicon, silicon oxide, titanium nitride, aluminum,
2 diamond, and polyimide. Polysilicon and silicon oxide provide excellent etch selectivity
3 relative to silicon nitride.

4 In the case of an aluminum substrate, a typical protective/masking layer may
5 comprise, but is not limited to, polyimide, titanium nitride, silicon oxide, and silicon nitride.
6 Polyimide, silicon oxide, and silicon nitride provide excellent etch selectivity relative to
7 aluminum.

8 In the case of an organic substrate, such as a polyimide, SILK, or BCB substrate, a
9 typical protective/masking layer may comprise, but is not limited to, silicon oxide, silicon
10 nitride, aluminum, and titanium nitride. Silicon oxide and silicon nitride provide excellent
11 etch selectivity relative to polyimide, SILK, and BCB.

12 The thickness of the protective layer 106 on interior surfaces of the shaped opening
13 104 is dependent on the size of the feature to be etched, the aspect ratio of the feature, and
14 the difference in etch rate between the protective layer and the substrate. For a given feature
15 size of 1 - 2 μm , a typical protective layer has a thickness ranging from about 1000 Å to
16 about 2000 Å. The required protective layer thickness for a particular application can be
17 determined with minimal experimentation, in view of the known art.

18 Referring to Figure 1C, the protective layer 106 may be anisotropically etched to
19 remove portions of the protective layer which overlie the bottom 108 of the shaped opening
20 104. Anisotropic etching is performed using apparatus and techniques known in the art.

21 A shaped cavity is then etched in the substrate underlying the shaped opening
22 according to the method of the invention. An etchant is selected which selectively etches
23 the substrate relative to the protective layer (*i.e.*, the substrate is etched at a much faster rate
24 than the protective layer) during the performance of the method of the invention. The
25 protective layer effectively preserves the profile of the shaped opening during etching of the
26 underlying shaped cavity.

27 According to the first step of a preferred embodiment method of the invention where

1 the substrate is silicon, gaseous etchant species are introduced through the shaped opening
2 in order to etch an underlying shaped cavity. Etching of the shaped cavity is generally
3 performed using a relatively high process chamber pressure within the range of about
4 20 mTorr and about 50 mTorr. Typically, a substrate bias voltage is applied, with the
5 amount of voltage depending on the degree of anisotropy (*i.e.*, vertical relative to
6 horizontal etching) desired. The higher the voltage, the more vertical the etch. When
7 increased vertical etching is desired, a higher bias power, typically ranging from about
8 20 W to about 200 W, is typically used. When increased lateral etching is desired, a lower
9 bias power, typically ranging from about 0 W to about 15 W, is typically used.

10 When the substrate is silicon and the protective layer is silicon oxide, etching is
11 typically performed using a plasma containing reactive fluorine species. The etchant plasma
12 is commonly generated from a source gas comprising SF₆ and argon, provided at a flow rate
13 which is process equipment dependent, and at an SF₆ : argon ratio within the range of about
14 10 : 1 and about 2.5 : 1. When a round shaped cavity is desired, an SF₆ : argon ratio of about
15 4 : 1 provides excellent results. Argon is used as a chemically inert carrier for the SF₆, and
16 ionized argon in conjunction with a substrate bias may be used to drive reactive fluorine
17 species generated from SF₆ down through the shaped opening and into the shaped cavity.
18 Further, high energy argon species provide physical bombardment of the substrate, assisting
19 in the etch process. The newly formed shaped cavity may be used as a reaction chamber
20 during subsequent etching steps.

21 The plasma source gas may further include an additive gas for the purpose of
22 controlling various properties of the shaped cavity, such as the shape or the surface finish
23 of the shaped cavity. Typical additive gases include, but are not limited to, O₂, HBr, Cl₂, and
24 N₂. For example, the addition of O₂ to the plasma source gas will result in a shaped cavity
25 having a roughened internal surface, whereas the addition of Cl₂ will lead to a smooth
26 internal surface. HBr provides effective profile control during etching of the shaped cavity.
27 Depending on the particular effect desired, the additive gas may be present during the entire

1 duration of the method of the invention, or it may be present only during a certain step or
2 steps. For example, if a particular finish is required on the surface of the final shaped cavity,
3 an additive gas such as O₂ or Cl₂ is typically added during the final finishing step described
4 below.

5 After the initial cavity etch step, a second etch step is performed during which the
6 process chamber pressure is decreased in order to allow the removal of etch byproducts from
7 the shaped cavity. This permits the subsequent introduction of fresh etchant species and
8 helps prevent the buildup of etch byproducts on interior surfaces of the shaped cavity. The
9 process chamber pressure used in the second etching step is typically about 30% lower than
10 the process chamber pressure during the initial cavity etch step. A process chamber pressure
11 within the range of about 10 mTorr to about 25 mTorr is typically employed during the
12 second etching step. By way of example, and not by way of limitation, when a round shaped
13 cavity is desired, decreasing the process chamber pressure by about 25 - 50% from the
14 process chamber pressure in the initial etch step provides excellent results. To obtain a
15 round shaped cavity, a bias power within the range of about 0 W to about 15 W is typical.
16 The plasma source gas used during the continued etching may be different, but for process
17 simplicity, it is preferably the same as that used during the initial cavity etching. An
18 additive gas, such as those described above, may further be included in the plasma source
19 gas during continued etching.

20 In an optional third etching step, the process chamber pressure is decreased still
21 further. The process chamber pressure used in the optional third etching step is typically
22 about 40 - 50% lower than the process chamber pressure used during the second etching
23 step. By way of example, and not by way of limitation, when a round shaped cavity is
24 desired, decreasing the process chamber pressure by about 50% from the process chamber
25 pressure used in the second etching step provides excellent results. A process chamber
26 pressure within the range of about 5 mTorr to about 12 mTorr is typically employed during
27 the optional third etching step. When the cavity is to be further expanded in a lateral

1 direction, a bias power within the range of about 0 W to about 10 W is typically used. For
2 process simplicity, the plasma source gas used in the optional third etching step is typically
3 the same as that used in the initial cavity etching.

4 In an optional etch finishing step, the process chamber pressure is increased to
5 provide the shaped cavity with an increased concentration of reactive species following the
6 reduction in concentration due to removal of the etch process byproducts during the second
7 and optional third etching steps. The process chamber pressure used during the etch
8 finishing step may be, but is not necessarily, lower than the process chamber pressure during
9 the initial cavity etch step. By way of example, and not by way of limitation, in the etch
10 finishing step, the process chamber pressure is typically increased to about 80 - 100% of the
11 process chamber pressure used during the initial cavity etch step. When a round shaped
12 cavity is desired, increasing the process chamber pressure to about 90% of the initial etch
13 step process chamber pressure provides excellent results. A process chamber pressure
14 within the range of about 18 mTorr and about 45 mTorr is typically employed during the
15 optional etch finishing step. When the emphasis in this step is on lateral etching, a bias
16 power within the range of about 0 W to about 15 W is typically applied. The plasma source
17 gas used in the etch finishing step is the same as that used in the first and second etching
18 steps.

19 The plasma source gas used in the etch finishing step typically comprises the same
20 components as that used in the first and second etching steps. However, increasing the
21 argon flow rate or lowering the ratio of fluorine species to argon in the plasma source gas
22 used in the etch finishing step provides a higher carrier flow to ensure that etchants will
23 travel into the cavity and react as desired. If no passivant species (such as HBr or O₂) are
24 added to the gas mixture, and if there is an adequate dilution of SF₆ in argon (as described
25 above), smoother interior cavity surfaces will be obtained. The addition of O₂ to the plasma
26 source gas will result in some roughness on the internal cavity surface. On the other hand,
27 Cl₂ addition should result in a smoother cavity surface.

In the etch finishing step, the SF_6 : argon ratio of the plasma source gas is typically within the range of about 5 : 1 and about 1.5 : 1. When a round shaped cavity is desired, an SF_6 : argon ratio of about 3 : 1 to about 2.5 : 1 provides excellent results.

Figure 1D shows the structure of Figure 1C after etching of shaped cavity 110 using the method of the invention. The shaped cavity 110 is etched to have a width B and a depth C, where the width B is equal to or greater than the depth C. As shown in Figure 1D, the shaped cavity 110 directly underlies and is in continuous communication with the shaped opening 104. The protective layer 106 effectively preserves the profile of the shaped opening 104 during etching of the underlying shaped cavity 106 using the method of the invention. The shaped cavity 110 shown in Figure 1D has been etched so that the width B is approximately equal to the depth C, resulting in the formation of a substantially round shaped cavity.

For purposes of comparison, the typical process conditions for each step of the preferred embodiment method of the invention are presented in Table One, below.

Table One. Typical Process Conditions During Etch of a Shaped Cavity

Process Condition	Step One	Step Two	Step Three	Step Four
Total Gas Flow (sccm)	≥ 100	≥ 100	≥ 100	≥ 1
SF_6 Flow Rate (sccm)	50 - 150	50 - 150	50 - 150	50 - 150
SF_6 : Ar Flow Rate Ratio	10 : 1 - 1.5 : 1	10 : 1 - 1.5 : 1	10 : 1 - 1.5 : 1	10 : 1 - 1.5 : 1
Substrate Temperature ($^{\circ}\text{C}$)	20 - 50	20 - 50	20 - 50	20 - 50
Process Chamber Pressure (mTorr)	20 - 50	10 - 25	5 - 12	18 - 45
Source Power (W)	600 - 900	500 - 800	350 - 650	500 - 800
Bias Power (W)	20 - 200	0 - 15	0 - 10	0 - 15

1 Any number of reductions in process chamber pressure, changes in substrate bias
2 voltage, and changes in plasma source gas composition and/or plasma source power may be
3 used to etch the desired shaped cavity.

4 Figure 2 shows a graph 200 of eccentricity (*i.e.*, the width of a shaped cavity divided
5 by its depth) as a function of the width of the overlying shaped opening, for shaped cavities
6 etched using a prior art etch process, represented by curve 202, and for shaped cavities
7 etched using the method of the invention, represented by curve 204. As shown in Figure 2,
8 for a given shaped opening width, a shaped cavity etched using the method of the invention
9 has a greater eccentricity than one that was etched using a conventional etch process. For
10 example, for a shaped opening width of 2 μm , a shaped cavity etched using the method of
11 the present invention has an eccentricity of about 1.08, whereas a shaped cavity etched using
12 a conventional etch process has an eccentricity of about 0.92. This indicates that the shaped
13 cavity etched using the method of the invention may be wider than it is deep, whereas the
14 shaped cavity etched using the conventional etch process must be deeper than it is wide.

15 The method of the invention is useful in many different applications. The method
16 of the invention can be applied to any application where it is necessary or desirable to
17 provide a structure having a shaped opening and an underlying shaped cavity having varying
18 shapes, and where it is necessary to maintain tight control over the dimensions of the shaped
19 opening. For example, the method of the invention can be used for micromachining of test
20 chips for performance of various chemical or biological assays (*e.g.*, genome testing),
21 wherein the testing reagents would be contained in a plurality of shaped cavities etched in
22 the chip. The method of the invention can also be used for micromachining of
23 electrostatically controlled nozzles for use in inkjet printers, wherein the ink would be
24 contained in the shaped cavity and the shaped opening would function as a nozzle. The
25 method of the invention allows for excellent control over the critical dimensions of the
26 shaped opening (*e.g.*, the diameter of the nozzle), providing for consistent and reproducible

1 micromachining of a variety of devices. Adapting the general method of the invention for
2 use in a particular application will be within the capability of one skilled in the art to which
3 that particular application belongs, without the need to perform undue experimentation.

4 Figures 3A and 3B, respectively, show examples of round (*i.e.*, width \approx depth) and
5 horizontal elliptical (*i.e.*, width $>$ depth) shaped cavity profiles that can be obtained using
6 the method of the invention.

7 Figure 3C shows a double spherical profile which is obtained by continued isotropic
8 etching of closely adjacent shaped cavities 302 and 304, in order to remove the substrate
9 material between the shaped cavities. By removing the substrate material between the
10 shaped cavities, a silicon "island" 306 is formed between shaped openings 308 and 310.
11 Either the silicon islands or cavities themselves can be used as waveguides for optical
12 interconnects in optoelectronic devices, or as a cantilever for an accelerometer, for example.

13 Using the method of the invention, with a shaped opening depth of from $0.8\ \mu\text{m}$ to
14 $2.0\ \mu\text{m}$, and a shaped opening width of from 3.5 to $4.5\ \mu\text{m}$, we have been able to form
15 shaped cavities having a width that is from 2.5 to 4 times greater than the width of the
16 overlying shaped opening, while maintaining a shaped cavity eccentricity of about 1 . We
17 have been successful in shaping a variety of features having an initial aspect ratio (*i.e.*,
18 shaped opening depth : shaped opening width) of less than about $3.5 : 1$. It is likely that we
19 would be able to accomplish similar results at even higher aspect ratios.

20 Preferably, the apparatus used to practice the present invention is adapted to be
21 controlled by a computer. Figure 4 shows a computer 400. Computer 400 comprises a
22 processor 402, memory 404 adapted to store instructions 406, and one or more ports 408.
23 Processor 402 is adapted to communicate with memory 404 and to execute instructions 406.
24 Processor 402 and memory 404 are also adapted to communicate with one or more ports
25 408. Ports 408 are adapted to communicate with an etch chamber 412. Chamber 412 is
26 adapted to carry out process steps in accordance with signals received from processor 402
27 via ports 408. Preferably, computer 402 can control the composition and feed rate of the

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1 etch process feed gases, the process temperature, the pressure in the chamber, the time
2 period for each process step, and other similar functions. Preferably, computer 402 is
3 adapted to receive measurements that describe the conditions in the chamber or a condition
4 of the substrate being etched, and adapt the process variables accordingly. This programmed
5 control of process variables enables production of a predetermined device etch profile as
6 required for a given use application.

7 One skilled in the art will recognize that a combination of etch steps at higher or
8 lower chamber pressures, using varying ratios of active etchant to inert gas in the plasma
9 source gas, and varying the plasma source power and substrate bias power can be used to
10 obtain a cavity having a predetermined shape. The above described preferred embodiments
11 are not intended to limit the scope of the present invention, as one skilled in the art can, in
12 view of the present disclosure, expand such embodiments to correspond with the subject
13 matter of the invention claimed below.

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